PULSED POWER DESIGN FOR A SMALL REPETITIVELY PULSED ELECTRON BEAM PUMPED KrF LASER*

D. Morton, D. Weidenheimer, T. DaSilva, J. Lisherness, T. Tatman, D. Spelts, I. Smith
Titan — Pulse Sciences Division

L. Schlitt *Leland Schlitt Consulting Services*
R. Sears *WTP Engineering*
J. Sethian, M. Myers *Naval Research Laboratory*
A. Mangassarian *Science Applications International Corp*
T. Albert *Commonwealth Technology Inc.*
W. Webster *Research Support Instruments.*

Abstract

Electra is a 700 J, repetitively pulsed, electron beam pumped Krypton Fluoride (KrF) laser that is developing technologies to meet the inertial fusion energy (IFE) requirements for rep-rate, efficiency, durability and cost [1]. We have designed a pulsed power system for the pre-amplifier in the Electra KrF laser system. This pre-amplifier is designed to produce 40 J of laser light in a 40 nsec pulse which will be used to provide the input to the main amplifier. The pulsed power for the front end will serve two roles. It will complete the laser system and it will serve as the demonstrator for the new advanced pulsed power topology that can meet the fusion energy requirements for durability, repetition rate, and cost. The pulsed power will first employ a gas-switched Marx, with anticipated maintenance intervals similar to that of the existing Electra main amplifier [2]. Later the driver will be replaced (circa 2006) with a solid-state-switched Marx generator [3].

The output requirements for the pulsed power driver into counter-streaming electron beam diodes are 20/40/30 nsec (t_{rise}/flat-top/t_{fall}), 150-175 kV, 60-80 kA per side and a 1.1 ohm nominal impedance. The pulser will operate in single-shot, burst, and continuous modes up to 5 pps, with 1 nsec (1 sigma) or less absolute timing jitter. Rather than build an individual driver for each e-beam diode as was done for the Electra main amplifier [2], a single pulsed power driver is coupled to the opposing electron guns via four liquid-filled Transit Time Isolators (TTIs). These TTIs are necessarily compound (oil/water/oil) in order to balance their electrical lengths against unequal mechanical lengths. The Marx is gas-insulated and charges a 1.1-ohm water pulse forming line (pfl) in less than 100 nsec. An output magnetic switch with a saturated inductance of less than 14 nH discharges the pfl into the four parallel TTIs. A set of four (2 each side) Z-stack inverted bushings connect the TTIs to the diodes.

This paper will present and discuss all major aspects of the electrical and mechanical design, as well as the anticipated performance from circuit simulations. The laser driver is scheduled to be delivered to and installed at the Naval Research Laboratory's Electra Laboratory in late 2003.

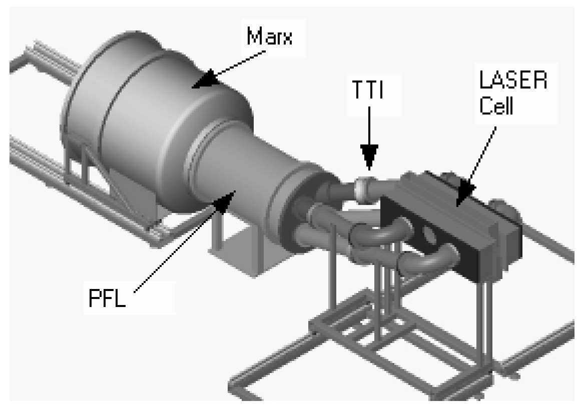

Figure 1. Small KrF laser driver.

I. DRIVER SPECIFICATIONS

Load Pulse Characteristics:	
Load voltage (high voltage mode)	175 kV
Load voltage (low voltage mode)	150 kV
Current (high voltage mode)	160 kA*
Current (low voltage mode)	>140 kA*
Voltage risetime	<20 ns (10-90%)
Voltage fall time	<30 ns (90-10%)
Flat top (power)	40 ns
Flat top variation (power)	+10%
Jitter: 1 ns, 1 sigma	
Repetition Rate: Single shot through 5 pps	
Misfires, Pre-fires and No-fires: <1 in 500	
System Lifetime:	
Spark gap lifetime (service interval): >10,000 shots (goal is 100,000 shots) Lifetime of other components: >100,000 shots (design point)	
*Both sides in parallel.	

II. DESIGN OVERVIEW

The required output pulse is formed using a 1.1 ohm pfl charged to ~340 kV and magnetically-switched into a set of four Transit Time Isolators (TTI). The TTI's are shaped to transport the electrical pulse to both sides of the KrF laser cavity. The inner conductors of the four TTIs are coupled to a pair of opposed electron guns through four Z- stack insulator feeds.

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14. ABSTRACT
Electra is a 700 J, repetitively pulsed, electron beam pumped Krypton Fluoride (KrF) laser that is developing technologies to meet the inertial fusion energy (IFE) requirements for rep-rate, efficiency, durability and cost [1]. We have designed a pulsed power system for the pre-amplifier in the Electra KrF laser system. This pre-amplifier is designed to produce 40 J of laser light in a 40 nsec pulse which will be used to provide the input to the main amplifier. The pulsed power for the front end will serve two roles. It will complete the laser system and it will serve as the demonstrator for the new advanced pulsed power topology that can meet the fusion energy requirements for durability, repetition rate, and cost. The pulsed power will first employ a gas-switched Marx, with anticipated maintenance intervals similar to that of the existing Electra main amplifier [2]. Later the driver will be replaced (circa 2006) with a solid-state-switched Marx generator [3].

15. SUBJECT TERMS

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The pfl is charged in about 100 ns by four parallel Marx generators. The Marx generators are SF_6 insulated and arranged in a low-inductance circular geometry. The four main Marx generators are triggered by a one-stage laser-triggered mini-Marx.

The system is designed for long-life rep-rate operation. Electrical stresses in the gas and liquids were kept low, generally less than 35% of JCM breakdown. Electrical stress in vacuum was kept to <80 kV/cm except near the cathode emitting surface where fields of up to 150 kV/cm were permitted. Extensive computer modeling was done in support of the design effort.

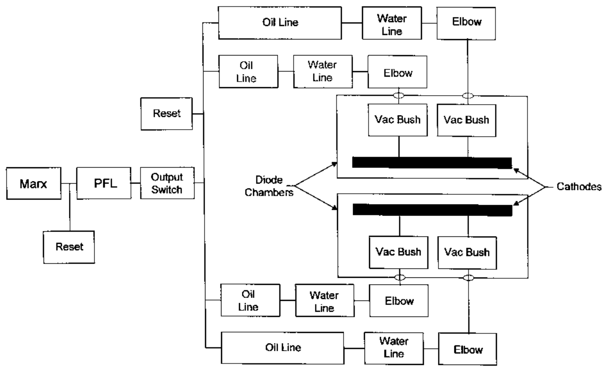

Figure 2. Block diagram of small KrF laser driver.

III. MARX AND TRIGGER

In order to use a single stage of magnetic pulse compression in the pulser design, a fast charge of the water pfl is required. This requires a low inductance Marx configuration to yield the 100 ns charge time needed. Four parallel Marx generators are arranged in a circular low-inductance geometry. Each stage utilizes two parallel capacitor stacks discharging through a single modified TPSD 40264 switch. The capacitor stacks are angled so they conform to the circular interior of the Marx enclosure. This arrangement forms a roughly coaxial geometry for the four Marx assemblies. Inductance of this parallel Marx assembly and common feed to the pfl is estimated at ~150 nH. The four Marxes are electrically triggered by a laser-switched single-stage mini-Marx located at the rear of the SF_6 pressurized (15 psig) enclosure. The mini-Marx trigger is designed to have jitter of less than 500 ps (1 sigma). The laser employed is a 30 mJ quadrupled YAG at 266 nm (see Figs. 3 and 4).

IV. PFL AND MAGNETIC SWITCH

A single magnetic output switch is used to switch the charged pfl into four parallel output TTIs. The water-insulated pfl is nominally 1.1 ohms with a peaker section near the output switch of about 0.74 ohms. Electrical length is ~28 ns (single transit).

The saturating magnetic output switch comprises four Metglas core assemblies built by Honeywell to specification. The cores are 1-inch wide by 0.8 mil thick 26055 tape. The material was annealed then co-wound with a single layer of 0.3-mil capacitor paper as insulation. The cores are wound on a 43.2 cm mandrel to a build thickness of 9.56 cm. Vacuum impregnation of the cores with transformer oil will occur in-situ. The output switch has a volt-sec product of ~16.2 mV-sec and a ΔB of ~2.7 Tesla.

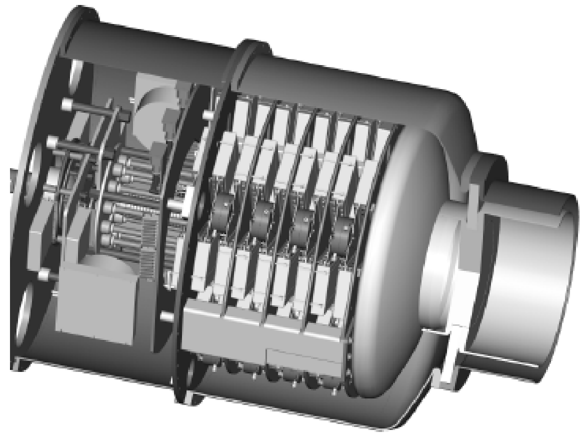

Figure 3. Cutaway view of Marx and trigger.

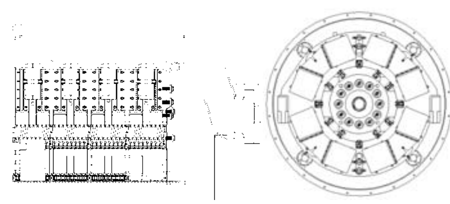

Figure 4. 2D views of Marx assembly.

The cores are arranged such that the voltage is divided across all eight core faces prior to saturation. Losses in the cores are small enough that simple convection face cooling and recirculation with the system's oil volume is sufficient. A D.C. reset current is applied using a pair of isolation inductors, one upstream of the switch in the Marx assembly and a second just downstream, as shown in Fig. 5. Field shapers are employed to keep insulating distances and the resulting inductance to a minimum. The estimated saturated inductance of the switch is ~14 nH and its mass is ~73 kg.

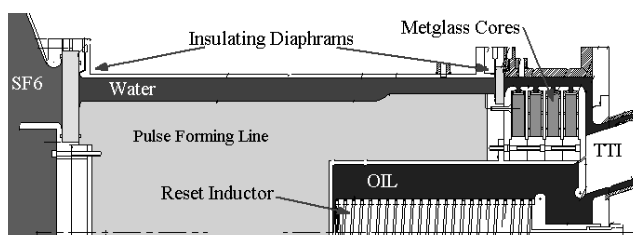

Figure 5. PFL, output switch and reset inductor.

V. TRANSIT TIME ISOLATOR (TTI)

Transmission of the output pulse to the pair of opposed electron guns is accomplished using four parallel Transit Time Isolators (TTI, Fig. 6). Since the pulsed power system was specified to be below the KrF laser axis, the TTIs are of unequal physical length. To match their transit times, a combination of oil and water dielectric sections is used. Starting at the output switch end, the initial section of each TTI is oil, followed by straight water section leading into an oil-insulated elbow. The double transit time of these TTIs is set to be approximately equal to the pulsewidth by varying the length of the oil and water sections. The impedance of the TTI sections is slightly higher than matched in order to lower the peak electric fields. The first oil section and water section are ~5.2 ohms rather than the ideal 4.4 ohm matching impedance. The oil elbows are 6.0 ohms due to tolerance concerns in fabrication. Circuit modeling shows that this slight mismatch has little effect on the pulse shape at the load.

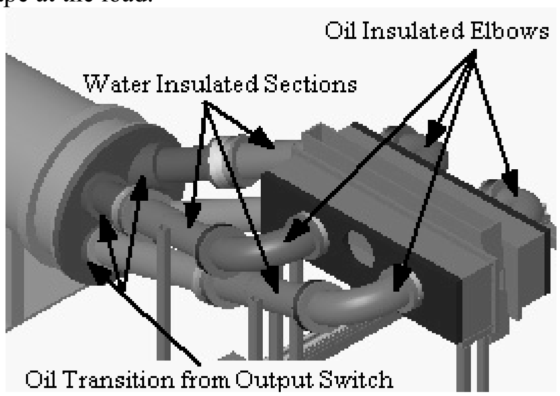

Figure 6. Transit time isolator geometry.

VI. VACUUM DIODE REGION

Each of the two opposing electron guns driving the KrF laser cell are fed through two ports. Each port is close coupled to the oil elbow end of one of the four TTIs. The transition into vacuum is accomplished using an inverted Z stack insulator and the interior of the Z stack is pressurized to 100 psig of SF_6. (See Fig. 7.)

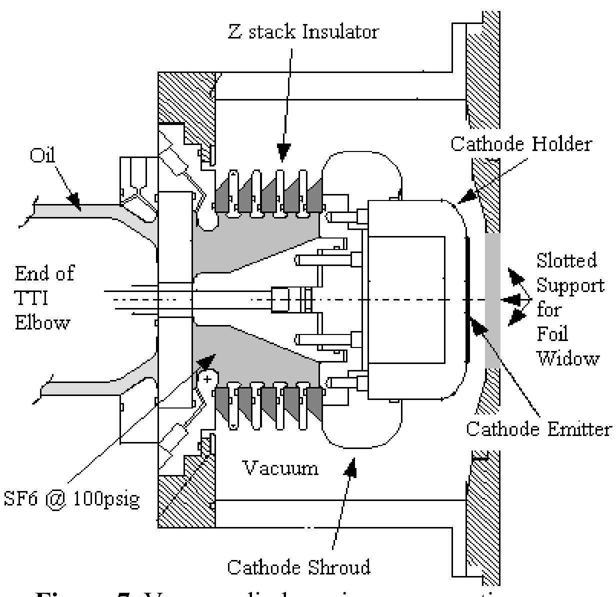

Figure 7. Vacuum diode region cross-section.

The cathode emitter is 10 cm x ~100 cm and the A-K gap can be adjusted by varying the position of the cathode holder. The cathode shroud, holder, Z-stack gradient rings and vacuum box are stainless steel and the Z-stack bushing insulators are Rexolite. Electric fields in the interior of the bushing (SF6) are < 80 kV/cm. Vacuum electric fields are kept to < 80 kV/cm to avoid emission. The peak fields on the cathode holder emitter plane are necessarily higher at ~150 kV/cm.

VII. DIAGNOSTICS

A comprehensive set of pulsed power diagnostics have been provided in the driver design. Voltage and current monitors have been incorporated into the vacuum diode region, TTIs, pfl, Marx and trigger generator. The Marx has additional current probes opposite each spark gap to aid in troubleshooting and jitter mitigation efforts. A fast automated fault-detection and shutdown circuit, based on newly available digital oscilloscope waveform mask technology will be employed. See Fig. 8 for diagnostic locations.

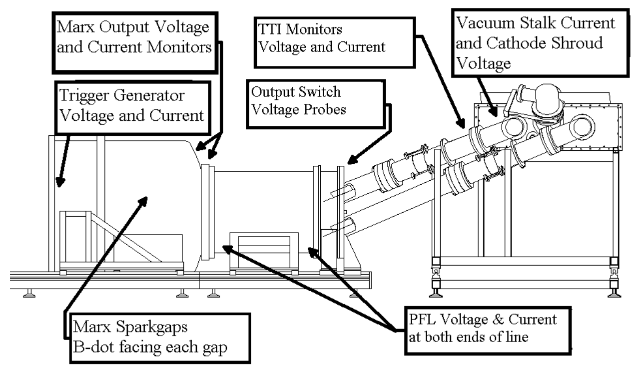

Figure 8. Diagnostic locations.

VIII. CIRCUIT SIMULATIONS

Extensive circuit simulations (Figs. 9-11) were performed during the design effort. The majority of these simulations were done using a transmission line based circuit simulation code. The models evolved in complexity throughout the design process. The latest models employed an NRL developed model for the electron beam load.

Circuit simulations for both normal and fault situations were performed. Sensitivity analyses that varied the TTI length, diode performance, Marx capacitance, magnetic switch core area, Marx inductance, Marx charge voltage and Marx switch timing were also performed.

IX. ELECTRIC FIELD DESIGN CRITERIA

Two sources of electrical design criteria were utilized/consulted; the accepted standard formulae, and the criteria used in designing the Electra main amp. Note that the latter does necessarily specify the minimum allowable fields. Rather they give limits that are known to be reliable in long-life, repetitively-pulsed applications.

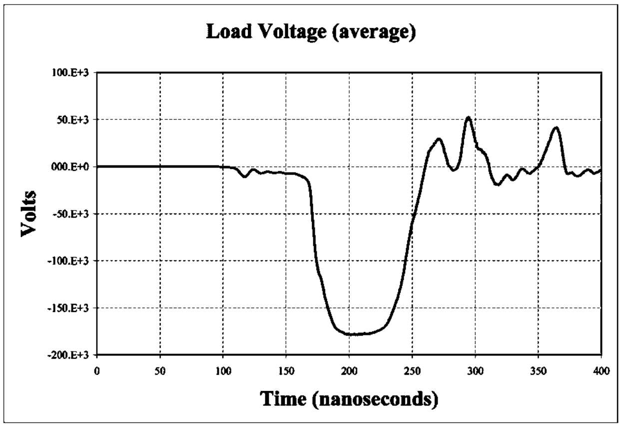

Figure 9. Average load voltage.

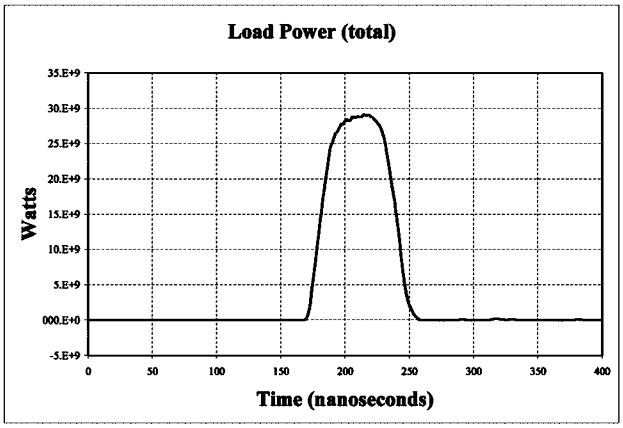

Figure 10. Total load power.

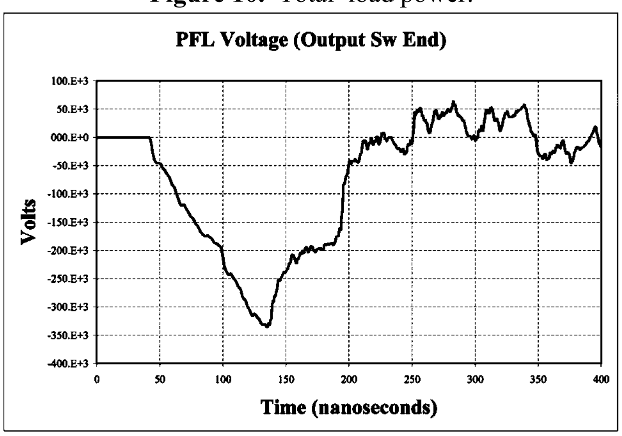

Figure 11. PFL Voltage (Output Switch End)

Formula used (F is in kV/cm)

Water:

$F+ = 230\, t^{-1/3}\, A^{-0.058}$

$F- = 560\, t^{-1/3}\, A^{-0.069}$

Oil:

$F+ = 480\, t^{-1/3}\, A^{-0.075}$

$F- = 670\, t^{-1/3}\, A^{-0.075}$

SF_6:

$F = 310\, p^{0.7}\, t^{-1/4}$

Vacuum:

$F = 175\, t^{-1/6}\, A^{-1/4}$

Criteria

Bulk Breakdown Design Limits:

Vacuum Cathode Holder:	150kV/cm†
Vacuum Cathode Shroud:	80kv/cm†
Vacuum Feed, 100psig SF_6:	108kV/cm‡
Marx Insulation, 15psig SF_6:	60kV/cm
Oil and Water:	E/F = 0.35 max, 0.30 typical

Interface Design Limits:

Vacuum:	E/F < 0.27 (per pair Z-stacks)†
Vacuum Feed SF_6:	52kV/cm‡
Marx Insulation SF_6:	35kV/cm
Water:	210kV/cm typical‡
Oil:	150kV/cm typical‡

†From Electra Design

‡Scaled for time dependence from Electra Design

X. SOLID STATE RETRO-FIT

A major part of the Advanced Electra pulsed power development is dedicated to developing the laser gated and pumped thyristor (LGPT). This advanced component is critical to meeting the cost, efficiency, size and lifetime requirements for KrF Laser IFE. A planned retro-fitting of the pulser's Marx generator with a solid state switched version is scheduled for 2006. The retro-fit will require lengthening the Marx tank by ~1/2 meter, but no other major dimensional changes are thought necessary at this time. When retro-fitted, this pulser will serve as a subscale demonstration of the components and topology that meet IFE requirements.

XI. SUMMARY

A compact high-reliability rep-rate KrF driver has been designed in support of the IFE program at NRL. The system utilizes a low-inductance fast Marx pulse charging a PFL in ~100 ns. The PFL is switched out by a Metglas output switch into a set of compound TTIs which carry the pulse to a pair of opposed electric beam guns. The Marx portion of the system is intended to be replaced with a solid-state based design in the future.

References

(1) J.D. Sethian, M. Friedman, J. Giuliani, R. Lehmberg, M. Myers, S. Obenschain, F. Hegeler, S. Swanekamp, in Inertial Fusion Sciences and Applications, edited by KA. Tanaka, D.D. Meyerhoffer and I. Meyer-ter-Vehn, Elsevier, NY, 495 (2002).

(2) J.D. Sethian et al., Pulsed Power For The Electra KrF Laser, 12th IEEE Pulse Power Conference, 1999.

(3) D. Weidenheimer et al., Proc. of Power Modulator Conference, Hollywood, CA, June 31-July 2, 2002.

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